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Inventor: THOMAS CHARLES POULTER

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COMPLETE SPECIFICATION

Improvements in or relating to Explosive Charges

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THE PATENT OFFICE,
21*st April*, 1958.

metallic, such as copper, steel, cast iron, aluminum or lead, or may be of glass or other non-metallic material. The cavity and liner are usually conical, hemispherical, or conforming to other surfaces of revolution about the longitudinal axis of the charge. Provision is made for initiating detonation of the charge on its axis at its rearward end.

Upon detonation f a conventional shaped charge, a detonation front advances through the charge in the direction of its major axis and impinges on the liner. By virtue of the extremely high particle velocities and pressures prevailing in the detonation front, the major portion of the liner is dynamically extruded in a pencil-like jet along the charge axis at extremely high velocity.

Because of the great penetrating power of this high-velocity jet, many applications, both military and industrial, of the shaped charge have been developed. An outstanding example of an industrial application is in the perforation of well casing and subterranean formations surrounding oil, gas and water wells.

Since its original development as a military

other theories (plastic deformation and brittle fracture) so that when one considers that it is possible to have the formation of the jet follow any one of three mechanisms, plus all possible combinations of these, it is not surprising that much confusion has resulted.

The problem is further complicated by the fact that there are no independent variables. It is generally recognized that the size, shape and composition and thickness of case surrounding it, the shape, thickness, and composition of the liner, stand-off distance, method of detonation of the charge, shaping of the detonation front, and the angle that the detonation front makes with the surface of the liner are all known to materially affect the performance of shaped charges.

There is, however, not a single one of these variables which can be considered to be an independent variable. On the contrary, the changing of any one of them changes an unknown number of the others, usually by an undetermined amount, so that without a rather clear understanding of the detonation process and the possible mechanisms of jet formation,

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We, BORG-WARNER CORPORATION, a corporation organised under the laws of the State of Illinois, United States of America, of 310 South Michigan Avenue, Chicago, Illinois, United States of America, and WELEX JET SERVICES, INC., a corporation organised under the laws of the State of Delaware, United States of America of 1400 East Berry Street, Fort Worth, Texas, United States of America, do hereby declare the invention, for which we pray that a patent may be granted unto us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates generally to explosive devices and is directed particularly to improvements in shaped charges. The term "shaped charge," as used herein and as generally employed in the art of explosives, designates a charge of high explosive having a cavity in its forward end which is lined with a layer of inert material. The liner may be metallic, such as copper, steel, cast iron, aluminum or lead, or may be of glass or other non-metallic material. The cavity and liner are usually conical, hemispherical, or conforming to other surfaces of revolution about the longitudinal axis of the charge. Provision is made for initiating detonation of the charge on its axis at its rearward end.

Upon detonation f a conventional shaped charge, a detonation front advances through the charge in the direction of its major axis and impinges on the liner. By virtue of the extremely high particle velocities and pressures prevailing in the detonation front, the major portion of the liner is dynamically extruded in a pencil-like jet along the charge axis at extremely high velocity.

Because of the great penetrating power of this high-velocity jet, many applications, both military and industrial, of the shaped charge have been developed. An outstanding example of an industrial application is in the perforation of well casing and subterranean formations surrounding oil, gas and water wells. Since its original development as a military weapon, the shaped charge has been the subject of extensive research, both analytical and experimental. For the most part, experimental research has been confined to cut-and-try procedures, and analytical research has been confined to the study of experimental data and the development of theories of the mechanism of jet formation which are consistent with and attempt to explain such data. Many conflicting and erroneous theories and explanations of the mechanism of jet formation have been advanced.

The mechanism of jet formation from a lined hollow charge is very complex, and there is probably no single explanation that will explain all of the experimental results to the exclusion of all other proposed theories. The most widely publicized mechanism is referred to as the hydrodynamic flow mechanism (Journal of Applied Physics 19, 563—1948). There are extensive experimental results to substantiate at least two other theories (plastic deformation and brittle fracture) so that when one considers that it is possible to have the formation of the jet follow any one of three mechanisms, plus all possible combinations of these, it is not surprising that much confusion has resulted.

The problem is further complicated by the fact that there are no independent variables.

It is generally recognized that the size, shape and composition and thickness of case surrounding it, the shape, thickness, and composition of the liner, stand-off distance, method of detonation of the charge, shaping of the detonation front, and the angle that the detonation front makes with the surface of the liner are all known to materially affect the performance of shaped charges.

There is, however, not a single one of these variables which can be considered to be an independent variable. On the contrary, the changing of any one of them changes an unknown number of the others, usually by an undetermined amount, so that without a rather clear understanding of the detonation process and the possible mechanisms of jet formation,

it is impossible to predict the performance of a new design of shaped charge. It is not surprising, therefore, that most of the development work to date has been conducted on a cut-and-try basis with usually very discouraging and inconclusive results.

To develop a set of rules for the design of an effective lined shaped charge based on so many interdependent variables would, of course, be impossible. A fundamental study of the detonation process and the mechanism whereby a metal liner is given its velocity when an explosive in contact with it is detonated, was therefore undertaken. In this manner a few least common denominators have been obtained which provide some useful design parameters.

From this it has been possible to evaluate the relations between the shape of the detonation front and the detonation velocity, and the relation between the detonation velocity and the detonation pressure. Still further studies of the detonation process permit an evaluation of the factors controlling the duration of the pressure associated with the detonation process. This pressure and its duration provide a means of determining the impulse imparted to the liner. This, coupled with the design of the liner, provides a means for determining the direction and velocity of the motion imparted to the various elements of the liner. Thus, it has been possible to better understand the complexity of jet formation and its control, which has resulted in the invention and development of a basis design of a shaped charge having vastly improved performance characteristics.

In the usual cut-and-try procedure there has been but little, if any, basic information on which to arrive at a modification of the construction of a charge, nor was there any basis for knowing whether the change in performance was a result of the variable which was intentionally changed or whether one of the dependent variables dominated any change there may have been in performance. It was therefore a matter of changing an unknown number of variables by an indeterminate amount to produce an accumulative effect that may be positive or negative.

From a knowledge of jet penetration it is possible to specify certain desirable properties of a jet and, with this as a basis, to establish many of the requirements for a jet-producing mechanism and through that to produce an effective charge design.

For good performance, the material in the jet should be concentrated into a compact, straight line jet of material moving at high velocity and having high density. There should be a maximum range in material velocity in the jet consistent with its having the highest attainable material velocity at the forward end of the jet, and decreasing at a reasonably uniform rate over the length of the jet to the minimum velocity that will produce effective penetration.

The necessity for this spread in jet velocity is to permit each element of the jet to complete its penetration of the target before the following element strikes the target.

Other things being equal, an increase in velocity of the forward end of the jet will increase the penetration of the jet. This is a very important factor since the percentage increase in penetration greatly exceeds the percentage increase in jet velocity necessary to produce it.

It is entirely possible that an increase in the average velocity of the material in the jet may reduce the penetration if that increase in velocity occurs primarily at the after-portion of the jet. In such a case each element of the jet would be striking the target before the preceding element had completed its penetration, and the piling-up effect may cause a large decrease in depth of penetration of as much as 75 percent, with only a minor increase in hole diameter. The extent to which the after-end of the jet can have its velocity increased is determined by the ability of each preceding element to complete its penetration. In order to obtain maximum penetration, the forward end of the jet should have the maximum obtainable velocity and each successive element should have the maximum velocity consistent with permitting the preceding element to complete its maximum penetration of the target before the succeeding element strikes.

With such specifications set up for an effective jet, it then becomes a matter of selecting the mechanism of jet formation and the charge design which will best lend itself to the production of such a jet.

While it is possible to design a lined shaped charge operating by a mechanism of jet formation whereby the high velocity forward end of the jet originates from the base of the liner, such a design does not permit taking advantage of certain novel features of the present invention.

From experimentation in which a conventional charge was modified in such a manner as to increase the velocity of the after-end of the jet by only a small amount, it was found that an appreciable decrease in penetration resulted. From this it was obvious that if any appreciable increase in penetration was to be accomplished, it would have to be through an increase in the velocity of the forward end of the jet. This meant devising techniques for increasing the velocity imparted to the metal of the apex of the liner.

Numerous attempts have been made to do this by means of peripheral detonation of the charge with generally unsatisfactory results, either because of the requirement of an excessive quantity of explosive or, if the quantity of explosive were reduced, because

the meeting of the converging detonation front over the apex of the liner would blast a hole through the liner along its axis and disrupt its normal jet formation. It is our discovery, however, that if the inert barrier by which peripheral detonation is generated is so constructed as to permit a delayed detonation to occur through its central portion, then instead of the converging peripheral detonation front meeting at the centre and blasting a hole through the apex of the liner, it will meet the delayed expanding detonation front in a circular area generally surrounding the apex of the liner and a generally spherical concave detonation front is developed which envelops the apex of the liner in a pressure manifold the sum of the pressures in the two detonation fronts.

Thus the forward end of the jet acquires a velocity far in excess of that produced by the conventional expanding spherical detonation front produced by single-point initiation. Due to the more nearly normal angle of approach of the peripherally generated detonation front over the central portion of the liner, the velocity over the central portion of the jet will be correspondingly increased. This will therefore permit an increase in the after portion of the jet, and hence the ratio of explosive to metal around the base of the liner can be increased over and above that which is permissible with the single-point-initiated charge.

We have discovered that the invention provides another very important advantage in that merely by a small shift in position of the apex of the liner closer to or farther away from the inert barrier, the diameter of the hole produced by the jet from this charge can be varied over a several-fold range, the maximum size hole being produced with the liner at the proper distance to cause the detonation front to conform in curvature to that of the liner apex.

A general object of the invention is therefore to provide an improved shaped charge the performance of which is characterized by more effective utilization of the energy available in the explosive than has heretofore been possible.

Another object of the invention is to provide an improved shaped charge which, upon detonation, produces a jet of higher overall velocity than has heretofore been attained.

A further object of the invention is to provide an improved shaped charge which not only produces a higher velocity jet than heretofore, but which is so designed that the velocity of successive elements of the jet is distributed over a range of velocities sufficiently wide to permit each element of the jet to most effectively expend its energy in effecting penetration of the target before the next succeeding element strikes the target.

Another object of the invention is to provide a shaped charge wherein the shape of the detonation front is altered in a predetermined manner by a body of inert material embedded in the explosive charge.

Yet another object of the invention is to provide a shaped charge wherein the size and shape of the hole produced in a target may be predetermined solely by the relative positions of certain of the charge components.

Another object of the invention is to provide a shaped charge incorporating a body of inert material embedded in the explosive charge, and wherein the size and shape of the hole produced in a target may be varied in predetermined manner by varying the distance between the inert body and the liner.

A still further object of the invention is to provide a shaped charge wherein, upon detonation, a detonation front is developed in the explosive which is characterized by a central concave front and a peripheral or annular convex front.

Still another object of the invention is to provide a shaped charge incorporating means for developing, upon detonation, a central detonation front and an initially separate and distinct peripheral detonation front, the time and space relation of the two fronts being such that they merge into a composite front having a concave central portion characterized by extremely high order pressure and particle velocity.

Yet another object of the invention is to provide a shaped charge wherein the optimum stand-off distance from the base of the liner to the target is substantially less than with charges heretofore developed.

Still another object of the invention is to provide a shaped charge wherein the mechanism of jet formation is such that the degree of interdependence of the various parameters of the charge is substantially less than in charges heretofore developed.

A still further object of the invention is to provide a shaped charge wherein the usual slug or "carrot" may, if desired, be substantially eliminated.

Generally speaking, based on our studies of detonation phenomena, we have discovered and developed an arrangement and procedure or technique whereby a detonation front of abnormally high pressure and velocity can be developed in the explosive charge rearwardly of the liner, with the central portion of the front being concave and conforming in shape very closely to that of the apex portion of the liner. This is accomplished by developing a combined peripheral detonation front and central detonation front in predetermined time and space relation to each other and to the apex portion of the liner. The merging of these detonation fronts produces a composite front in which the pressure and the detonation velocity greatly exceed the sum of the individual pressures and velocities of the two

fronts. Not only is it possible to "tailor" the shape of this composite front to conform substantially to liner apices of different curvatures, but it is also possible with the improved charge design to produce a wide range of target hole sizes with the same liner shape, by the simple expedient of slight changes in the position of the liner, involving merely a slight change in loading technique.

The manner in which the foregoing and other objects may be accomplished will become apparent from the following detailed description of a presently preferred embodiment of the invention, reference being had to the accompanying drawing wherein:—

Figure 1 is a central longitudinal sectional view of a shaped charge embodying the invention; and

Figure 2 is an enlarged view similar to Figure 1, illustrating successive stages of propagation of the individual detonation fronts, their merger into a single composite front, the progressive change in shape of the composite front and its impingement on the apex portion of the liner.

Referring to Figure 1, a charge case 1 is herein shown as cylindrical but may be of any other desired shape symmetrical with respect to the charge axis, and is preferably of metal such as steel, cast iron or aluminum but may if desired be of non-metallic material such as any of the commonly used plastics. A liner 2 of copper or other suitable material is mounted in the case in a conventional manner. As shown, the apex portion 3 of the liner is rounded and the side portions of the liner are of gradually decreasing curvature. It will be understood, however, that the specific shape of the liner does not constitute a significant aspect of the present invention and various other shapes may be employed if desired.

Rearwardly of the liner the case 1 is filled with an explosive 4 having a high detonation rate, such as TNT, Cyclotol, etc. Embedded in the explosive 4 adjacent the rear wall of the case is a barrier 5 of inert material such as steel or other metals or non-metals. The barrier 5 is disposed transversely of the charge and is symmetrical and coaxial with the case and liner. As shown the barrier 5 is of uniform thickness and is preferably in the form of a segment of a sphere, although other shapes which are symmetrical with the axis of the charge may be employed, such as conical, paraboloidal, ellipsoidal, or a flat disc. The diameter or transverse dimension of the barrier is less than the internal diameter of the case 1 thereby providing an annulus 6 of explosive surrounding the periphery of the barrier and joining the bodies of explosive at the forward and rearward sides of the barrier. In order to provide a layer of explosive 7 of uniform thickness between the barrier and the rear wall 8 of the case 1, the latter is preferably also in the form of a segment of a sphere or of other shape conforming to that of the barrier.

A tubular socket 9 projects from the rear wall of the case 1 in coaxial relation thereto, and is perforated transversely at 10 to receive a length of Primacord 11 or other detonating fuze. A booster pellet 12 is seated in the socket 9 between the Primacord 11 and the rear wall of the case, and is in direct contact with the explosive 7 through an opening 13 in the rear wall 8, it being understood that the explosive also fills the opening 13. The opening 13 should be small enough to assure concentricity of the detonation front.

It will be apparent that detonation of the Prima-cord 11 will detonate the booster 12, which in turn initiates detonation of the explosive 7 at the opening 13. Referring to Figure 2, the detonation front developed at the opening 13 initially expands spherically until it strikes the rear wall of the barrier 5, whereupon it is converted into a radially expanding circular front progressing through the layer 7 of explosive, successive positions of the front being indicated at 15, 15*a* and 15*b*.

Upon reaching the periphery of the barrier, the detonation front progresses therearound and forwardly through the annulus 6 of explosive. As it passes the forward peripheral edge of the barrier and enters the main body of explosive 4 it is free to expand both forwardly and radially inwardly toward the axis of the charge. Hence, the forward and inward portion of the front assumes the form of a portion of the surface of a torus, as indicated by the corresponding pairs of arcuate dotted lines 16, 16*a* and 16*b*.

Meanwhile the detonation of the explosive in contact with the rear surface of the barrer 5 has generated a shock pulse in the material of the barrier. This shock pulse, initiated at a point on the axis of the charge, progresses forwardly through the barrier as indicated at 17, 17*a*, 17*b* and 17*c*, to the forward, concave surface thereof. Also, as the detonation front indicated at 15, 15*a* and 15*b* expands through the explosive layer 7, it rolls along the rear surface of the barrier 5 and generates a radially progressing series of shock pulses in the barrier, which progress forwardly through the barrier.

Whether or not the explosive in contact with the forward surface of the barrier 5 will be detonated by the shock pulse transmitted through the barrier, and whether the detonation is low-order or high-order, depends, generally speaking, on the intensity of the shock pulse as it reaches the forward surface of the barrier and on the sensitivity of the explosive in contact therewith. The intensity of the shock pulse after it passes through the barrier depends on the material of the barrier, the thickness of the central portion thereof, and the thickness of the central portion of the

layer 7 of explosive which generates the shock pulse.

By way of example, in tests wherein the explosive used was waxed "RDX," a military form of cyclonite ($CH_3.N.NO_2$), it has been determined that with a barrier 5 of steel and with a 1/16 inch thick layer 7 of explosive which is detonated by a booster such as the pellet 12, if the thickness of the central portion of the barrier is 3/16 inch or greater the explosive in contact with the forward surface will not be detonated by the shock pulse. If the central portion of the barrier is 1/10 inch to 1/8 inch in thickness, the shock pulse transmitted through it will initiate low-order detonation of the explosive at the forward side of the barrier. If the central portion of the barrier is substantially less than 1/10 inch in thickness the shock pulse will initiate high-order detonation of the explosive at the forward side thereof.

On the other hand, from tests with charges in which the type of explosive, the material and thickness of the barrier 5, and the thickness of the layer 7 of explosive were identical with those referred to in the preceding paragraph, but in which the booster pellet 7 was omitted and detonation was initiated directly by Primacord, it was found that the optimum barrier thickness from the standpoint of depth of penetration was 0.059 inch, as compared to 0.10 to 0.125 in the previously mentioned test results. This may be explained by the fact that the booster pellet 12 constitutes in effect an additional thickness of explosive behind the central portion of the barrier. This points up the important influence which the thickness of the explosive exerts on the initial velocity of the shock pulse developed in the barrier.

It is thus apparent that by the selection of a barrier of appropriate material and thickness, or by varying the effective thickness of the explosive behind the barrier, any one of three distinctly different detonation front conditions may be produced in the explosive forwardly of the barrier—(a) a converging, high-order peripheral detonation front only; or (b) a converging, high-order peripheral detonation front and a delayed, expanding, low-order central detonation front; or (c) a converging, high-order peripheral detonation front and a delayed, expanding, high-order central detonation front.

The respective characteristics of the two distinct types of detonation known as "high-order" and "low-order" detonation are well known to those familiar with explosives and have been delineated in many publications dealing with explosives. A well-known example of such publications is "Detonation in Condensed Explosives" by J. Taylor, Oxford Press, 1952, London, England. An explanation and discussion herein of those phenomena is therefore not deemed necessary.

As has been pointed out previously, a converging peripheral detonation front alone (condition (a) above) is not conducive to proper jet formation. The apex of the liner is not the first portion of the liner to be given a velocity as is the case with single-point detonation. Instead, the detonation front first contacts a ring of material farther down on the liner. Since this first contact is normal to the surface, that portion of the liner will be given a high velocity. As the detonation front rolls along the surface of the liner in the direction of the apex, the angle of approach becomes less than 90° and the material is given a lower velocity than the portion of the liner first contacted. This lower-velocity material is projected into the region where the jet is being formed and disturbs the jet formation. However, as the detonation front reaches the apex, it converges and meets at a point. Such a meeting of detonation fronts produces, at that point, a pressure estimated to be in excess of fifty million psi. With such a pressure at a point, a jet of extremely high-velocity material is projected into the zone where the jet proper is being formed, and since the lower velocity material has already been projected into that zone, the collision of the extremely high-velocity material with it tends to disrupt the process of jet formation. Although the process of jet formation proceeds in an orderly manner in the lower portion of the liner, the disturbance in the formation of the apex of the jet has been such as to prevent its superior performance. This interference can be prevented to some extent if the distance between the zone of peripheral initiation and the apex of the liner is increased, which accounts for the belief that in order for peripheral detonation to function properly, an excessive amount of explosive is required.

We have discovered that if conditions are such as to produce a high-order central detonation front and a high-order peripheral detonation front, the collision of two such high-order fronts produces a sharply defined annular zone of extremely high pressure. If the liner be located close enough to the barrier to subject any portion of the liner to the effect of this sharply defined, annular high-pressure zone, there results a marked decrease in the effectiveness of the jet. This is attributed to the sharp boundary-cutting effect of the annular high-pressure zone on the liner, producing a sharp discontinuity in the velocity gradient of the jet. On the other hand, if the liner be located far enough away from the barrier to avoid the sharp boundary-cutting effect of the high-order detonation collision zone, the performance of the charge is strikingly similar to that of a conventional charge having single-point initiation. This indicates that the axial spacing between the liner and the barrier is so great that the initially centrally concave detonation front has been converted to a conventional convex front

before it reaches the apex of the liner, and hence that the advantageous effect of the barrier has been dissipated. It therefore appears that less advantageous results are obtained when the parameters of the components of a barrier-type charge are such as to produce central and peripheral detonation fronts which are both of high-order.

One of the most important and most significant aspects of the invention is our discovery that with the proper relationship between the type of explosive, the barrier material and thickness, and the thickness of explosive behind the central portion of the barrier to develop a low-order central detonation front and a high-order peripheral detonation front at the forward side of the barrier, marked and unprecedented improvements in charge performance from any standpoints, as well as several other outstanding advantages, can be achieved. These improvements and advantages, which will be explained more in detail hereinafter, are briefly as follows:

(a) greatly increased depth of target penetration and volume of target hole for a given amount of explosive;
(b) wide variation in the cross-sectional area of the target hole by varying only the amount of explosive while maintaining all other components the same;
(c) substantial reduction in the number of parameters which effect performance, making possible the development of a simple equation defining the relationship of the significant parameters;
(d) substantial reduction in optimum standoff distance (from base of liner to target);
(e) substantial elimination of the usual slug or "carrot."

The mechanism of development of the initially separate, low-order central detonation front and high-order peripheral detonation front, their merger into a composite front having a concave central region, and the progressive change in the contour of this front, will be made clear by reference to Figure 2 of the drawing. as shown therein, the dot-and-dash lines 18, 18*a* and 18*b* represent successive positions of the low-order expanding central detonation front initiated by the shock pulse transmitted through the barrier 5. The meeting of this front with the converging peripheral detonation front, indicated at 16, 16*a* and 16*b* produces a composite front which initially comprises the portions 16*b* and 18*b*.

The juncture of the central front 18*b* with the peripheral front 16*b* initially produces an annular, sharply concave region indicated at 19, wherein the radius of curvature is very small and the pressure and the particle velocity are considerably higher than at other points on the composite front. Consequently this portion of the front has a greater velocity than the remainder of the front, resulting in a progressive increase in radius of curvature in that region.

It will be observed that the peripheral portion 16*b* of the initial stage of the composite front is considerably in advance of the central portion 18*b*. This results from the cumulative effect of several time-delays occurring in the generation of the central front 18*b*. The first time lag occurs in imparting velocity to the surface particles of the barrier 5 at the interface with the explosive layer 7, to generate the shock pulse 17. Another time-delay is the result of the lower velocity of the shock pulse 17 in comparison with that of the high-order detonation pulse travelling through the explosive around the barrier. The shock pulse velocity in a steel barrier is only about one-fourth that of the detonation pulse. Consequently the successive positions of the shock pulse front indicated at 17, 17*a*, 17*b* and 17*c* approximately correspond respectively to the positions 15, 15*a*, 15*b* and 16 of the detonation front.

Another time-delay occurs in the initiation of detonation of the explosive at the central forward side of the barrier 5 by the shock pulse. Lastly, if the barrier is such as to cause the shock pulse to generate low-order detonation of the explosive, the considerably lower velocity of the low-order detonation pulse will cause an additional time delay. Thus, the location of the low-order detonation front indicated at 18 will correspond in time to that of the shock pulse front indicated at 17*c* which, as stated above, corresponds to the location of the peripheral detonation front indicated at 16. As the front 18 moves successively to the positions 18*a* and 18*b*, the front 16 moves to the positions 16*a* and 16*b*.

It will be understood that the aforementioned time-delays are of infinitesimal order, but nevertheless sufficient to cause the formation of a composite front such as 16*b*, 18*b* having a peripheral portion 16*b* in advance of its central portion 18*b*.

An important and advantageous characteristic of the meeting of a low-order central detonation front and a high-order peripheral detonation front is that it does not produce a sharply defined, extremely high pressure zone as in the case of the collision of two high-order detonation fronts. Instead of a sharply defined annular zone of extremely high pressure resulting from the collision of a high-order, expanding central detonation front and a high-order, converging peripheral detonation front, which, as stated previously, produces a sharp boundary-cutting effect, the meeting and merging of a low-order central detonation front with a high-order peripheral detonation front produces a zone of considerably lower pressure, distributed over the entire central area of the resulting composite

front. This distribution is the result of a merging, as distinguished from a collision, of the two fronts.

As the composite front advances toward the apex of the liner 2, the concave annular region 19 which joins the central portion with the peripheral portion gradually flattens out and eventually merges with the central and peripheral portions to produce a concave-convex front, as indicated successively at 20 and 21. At a certain distance forwardly of the barrier 5, this front has a central concave portion substantially conforming to the curvature of the spherical apex portion of the liner 2, as indicated at 22. In the illustrative embodiment the liner is positioned with its apex at the proper distance from the barrier 5 to achieve this conformity. Accordingly, the entire spherical apex portion of the liner is subjected simultaneously to the extremely high pressure and velocity of the concave central portion of the detonation front. A relatively large portion of the liner is therefore concentrated in the forward, maximum velocity portion of the jet. This is in striking contrast to the jet formed by a charge in which detonation is initiated at a single point and the convex detonation front travels along the axis and strikes the apex of the liner. In the latter case only a relatively small amount of the material of the liner is concentrated in the forward, maximum velocity portion of the jet.

Inasmuch as the particle velocity at any point on the detonation front is a maximum in a direction normal to the front at that point, as indicated by the arrows 23, and inasmuch as in the arrangement shown in Figure 2 each point on the central concave spherical portion of the front impinges on the apex of the liner in such normal direction, the maximum velocity is substantially simultaneously imparted to the entire mass of that portion of the liner. As the detonation front advances beyond the last position shown in Figure 2, the angle of approach of the front to the side portion of the liner progressively decreases from 90°. Other factors being equal, this serves to reduce the velocity imparted to successive portions of the liner material. Furthermore, the thickness of the explosive, measured normal to the surface of the liner, decreases forwardly and has a further reducing effect on the velocity imparted to successive portions of the liner. The desired velocity gradient along the jet is thus attained, while still providing an average velocity considerably higher than that obtained previously, by virtue of the extremely high velocity of the forward portion of the jet.

By virtue of the higher pressure and velocity of a concave detonation front, as compared to that of a planar or convex front, the curvature of the central concave portion 22 of the front decreases as the front advances beyond the last position shown in Figure 2. Hence, if the liner 2 were positioned with its apex farther from the barrier 5 the concave central portion of the front would be of less curvature than that of the apex of the liner at the instant of impingement of the front on the liner apex. Consequently the front would strike the liner first at a point on the axis of the charge, followed by successive impingement over an expanding spherical area of the liner apex.

Conversely, if the liner 2 were positioned closer to the barrier 5 than as shown in Figure 2, the curvature of the central concave front would be greater than that of the liner apex and consequently the initial contact of the detonation front with the liner apex would be along a circular concentric path spaced from the axis. In each of these instances the portion of the liner forming the forward portion of the jet would be extruded in a mass of smaller diameter than under the condition shown in Figure 2, and a smaller hole would be formed in the target.

It is thus apparent that the target hole size may be varied over a considerable range by the simple expedient of varying the axial distance between the liner and the barrier, and using identical charge components except for a variation in the amount of explosive. This is an important and highly advantageous feature of the present invention.

The foregoing statements concerning variation of target hole size have been confirmed experimentally. Numerous tests have been conducted under simulated oil well conditions, wherein the targets were sections of well casing of .375″ wall thickness, surrounded by aged cement simulating oil-bearing rock formation such as sandstone or limestone. Typical results are shown in Table I below, which shows a comparison of target hole sizes obtained in the well casing with charges which were identical except for variation of the axial distance between the liner and the barrier and a corresponding variation in the amount of explosive.

TABLE I.

Weight of Explosive (grams)	Dia. of Hole in Well Casing (inches)	Depth of Penetration in Formation (inches)	Volume of Hole (cu. in.)
15	.462	9.1	3.1
19	.550	9.8	3.67
23	.740	10.65	4.25
26	.437	9.5	2.50
29	.375	9.0	3.00

The charges used in the foregoing and numerous other tests are typical of charges which have been developed embodying the present invention, and in which emphasis has been placed on the diameter of the hole produced in the target, rather than on obtaining maximum penetration irrespective of hole size. By way of example, structural details of the charges used in the tests referred to above are given as follows:—

The case 1 is of standard $1\frac{1}{4}$ inch inside diameter steel tubing of 1/16 inch wall thickness, the rear wall 8 being formed of 11 gauge steel plate pressed with a $2\frac{1}{4}$ inch ball to a 1-1/8 inch radius of curvature and welded to the end of the case. The booster socket 9 is welded to the rear wall 8 and is of a suitable size and shape to accommodate the particular type of booster pellet 12 to be used. The barrier 5 is made from circular blanks of 11 gauge steel, pressed with a 2 inch ball to a 1 inch radius of curvature. The liner 2, of copper, has a 50° included angle with an apex radius of curvature on the inside of $\frac{1}{2}$ inch and a uniform wall thickness of 0.030 inch. The outside diameter of the base of the liner is about 0.003 inch larger than the inside diameter of the case, thus providing an interference fit to hold the liner snugly in position when pressed into the case.

The explosive charge 4 and the layer of explosive 7 rearwardly of the barrier 5 are waxed, granular "RDX" pressed to 10,000 psi. The loading operation is performed in two steps—first, 4 grams of explosive are pressed to form the layer 7, about 1/16 inch in thickness; the barrier is then inserted and the remainder of the charge is then loaded and pressed. The liner 2 is then pressed into snug contact with the main charge. The quantity of explosive in the main charge 4 will vary in accordance with the target hole size desired, as pointed out hereinabove. In the tests from which the results given in Table I above were obtained, the explosive weights of 15, 19, 23, 26 and 29 grams represent the total amount of explosive including the 4-gram layer 7.

It should be pointed out that it is not necessary to directly determine the axial distance between the barrier 5 and the apex of the liner 2, inasmuch as this distance is relative and is indirectly determined by the amount of explosive in the main charge 4. It is, however, necessary to determine experimentally the performance data of a charge of a particular design. An important characteristic of shaped charges embodying the present invention is that by virtue of our newly developed and entirely different mechanism of jet formation, the number of variables which materially affect charge performance, and which are changed by unknown amounts by changing other variables, has been greatly reduced. For example, an analysis of a large quantity of test data involving identically-designed charges of different sizes has revealed that the ratio of the depth of penetration to the base diameter of the charge liner is fairly constant over a reasonably wide range of base diameters of the liners. This ratio, which is an effective criterion of charge performance, may be expressed by:

$$K = P/d \qquad (1)$$

where:

P = depth of penetration of the target;
d = base diameter of the liner; and
K = ratio of depth of penetration to base diameter of the liner.

In a series of identically-designed charges of different sizes, the weight of explosive is proportional to the cube of the base diameter of the liner; or

$$W = Cd^3 \qquad (2)$$

or, expressed differently,

$$C = W/d^3 \qquad (3)$$

where:

W = weight of explosive;
C = weight of explosive in a charge whose base diameter of the liner is unity.

By combining equations (1) and (2), the following equation is derived:

$$W = C(P/K)^3 \qquad (4)$$

It will be apparent that by substituting in equations (1) and (3) the values W and d of a given charge exemplary of a series of the same design, and the value of P obtained from test firings of such a charge, the values of the constants C and K for that design may be determined. When these values of C and K are substituted in equation (4) above, one may determine either the penetration which may be expected from a charge of the same design having a weight of explosive W, or the weight of explosive W required to produce a desired penetration.

By the use of the foregoing equations in conjunction with test data from a few types of special-purpose charges of varying designs, it is thus possible to select the proper design for a particular purpose and to calculate the actual charge dimensions for a particular size of the selected design. The determination of the proper amount of explosive required to produce a desired target hole size with a selected design and charge size, if hole size should be a major consideration, can be accomplished by a few simple experiments which involve merely varying the amount of explosive between liner and barrier while using otherwise identical charge components. The effect of such variance within the range of feasible hole sizes is minor.

From the foregoing detailed description of one embodiment of the invention and the

accompanying description of the newly developed and proven theories of detonation and of jet formation in a shaped charge, it will be evident that by following these teachings a shaped charge having superior performance characteristics may be produced. Furthermore, by the application of the principles set forth hereinabove to the design of shaped charges for various uses and purposes and to meet various conditions of use, it is possible to "tailor" a charge design for optimum performance under a given set of conditions.

For example, if a large hole is desired, the charge may be designed to provide a relatively large radius of curvature of the liner. Application of the principles of this invention permits the concentration of a large portion of the material of the liner apex in the forward, maximum-velocity portion of the jet. Thus the liner is disposed at the proper distance from the barrier to cause the curvature of the central concave portion of the detonation front to substantially conform to the curvature of the liner apex at the instant of impact of the detonation front on the liner apex. Conversely, should a smaller hole size be desired, a smaller radius of curvature would be utilized, and again in order to attain maximum efficiency the liner would be disposed at a distance from the barrier to permit conformation of the detonation front to the liner apex curvature.

Reference has previously been made to the three distinctly different detonation front conditions produced at the forward side of the barrier, depending on the type of explosive, the material and thickness of the barrier, and the thickness of the explosive behind the central portion of the barrier. In addition to the criterion afforded by the pronounced increase in target penetration when conditions are such as to produce a low-order central detonation front and a high-order peripheral detonation front, another and even more positive and reliable indication is available from test firing of charges from which it can be definitely determined which of the three detonation front conditions were produced. This indication is afforded by an examination of barriers after test firing of the charges.

Inasmuch as the time interval between detonation of the rearward layer 7 of explosive and detonation of the main explosive charge 4 is infinitesimally small, of the order of one micro-second, the forward velocity which would otherwise be imparted to the barrier 9 by detonation of the explosive layer 7 is counteracted and offset by the rearward velocity imparted thereto by detonation of the main charge 4. Accordingly upon firing the charge the barrier remains practically motionless and, in tests with charges having steel barriers, the barriers can be found in close proximity to the original position of the charge, intact and undamaged by impact on any objects in the vicinity. The physical appearance of the barriers will, however, undergo certain specific and distinguishable changes, depending on which of the three aforementioned detonation front conditions is produced.

Thus, if conditions are such as to produce a high-order central detonation front and a high-order peripheral detonation front, the sharply defined annular zone of extremely high pressure produced by the collision of these two high-order fronts forms a sharply defined circular cut or groove in the forward surface of the barrier close to the periphery thereof. This definitely identifies this condition.

If, however, conditions are such as to produce the preferred combination of a low-order central detonation front and a high-order peripheral detonation front, the distributed zone of moderately higher pressure produced by the merger of these two fronts forms a shallow depression of substantial width in the forward surface of the barrier. Because of the relatively lower velocity of the low-order front, as compared to that of a high-order front, the region of initial meeting of the fronts in this instance is at a shorter distance from the axis than in the case of the collision of high-order central and peripheral fronts. Hence both the location and the form of the indentation or groove provide positive means of distinguishing between the two above-mentioned conditions.

Lastly, if conditions are such as to prevent the development of a central detonation front by shock pulses transmitted forwardly through the barrier, the extremely high pressure developed along the axis of the charge, by the converging of the peripheral front and its meeting at a point on the charge axis, produces a high velocity jet in both directions along the charge axis. The rearwardly directed jet blasts a large hole through the central portion of the barrier, but there is no indication on its forward surface of a collision or merging of detonation fronts, as in the other two cases. This condition can thus be identified.

It has also been stated previously that the optimum stand-off distance (from the base of the liner to the target) of shaped charges embodying the present invention is substantially less than with charges heretofore developed. This is another result of the different mechanism of jet formation. According to the generally accepted theory of the mechanism of jet formation in a conventional shaped charge having single-point initiation of the main charge, the liner is collapsed radially inwardly upon itself and the forward portion of the jet contains liner particles which are extruded forwardly from the centre of the collapsed liner by the extreme inward collapsing pressure. This extrusion of liner material

occurs while the collapsed liner is being propelled forwardly at a lower velocity than that of the extruded material, and it is believed to be for this reason that a stand-off approximately equal to the diameter of the charge must be provided in order to permit this mechanism to function properly.

On the other hand, in a charge embodying the present invention a substantial portion of the liner at the apex end is projected forwardly along the axis at an extremely high initial velocity and, from the start of jet formation, forms the forward portion of the jet. The effective stand-off in this instance might well be measured from a point near the apex of the liner rather than from its base. Hence the stand-off distance from the base of the liner to the target need be merely a small fraction of that required for conventional charges. This is obviously a distinct advantage in uses of shaped charges which impose severe restrictions on the permissible over-all length of the charge plus the stand-off distance.

Yet another important characteristic of shaped charges embodying the present invention, which is of particular advantage in certain fields of use, is that the usual slug or "carrot" may, if desired, be substantially eliminated. This is believed to be due primarily to the following factors: first, a large portion of the liner, starting at its apex end, is projected into the forward maximum-velocity portion of the jet and is disintegrated during the process of penetration into the target; secondly, the enhanced velocity gradient along the jet assists in disintegration of the intermediate and base portions of the liner; and lastly, because of the more efficient utilization of the available energy of the explosive by the higher average velocity of the jet and the improved distribution of velocity along the jet, it is possible to use a liner of less wall thickness than is required for optimum performance of a conventional shaped charge, resulting in a reduced amount of residual liner material to form a slug.

While there has been illustrated and described herein but a single embodiment of the present invention, it will be apparent to those skilled in the art that various modifications and changes in the shape, material and relative positions of the various components may be made without departing from the essence of the invention. It is intended to cover herein all such modifications and changes as come within the true scope and spirit of the appended claims.

What we claim is:—

1. A shaped explosive charge having a cavity at its forward end, a liner of inert material lining said cavity, and a detonator at its rearward end, characterized by a barrier of inert material embedded in the explosive rearwardly of said cavity and having explosive in contact with all surfaces thereof whereby a detonation front initiated in the explosive rearwardly of said barrier will propagate at high order around said barrier and initiate a high order annular detonation front in the explosive at the forward side of said barrier, said barrier being substantially in the form of a disc disposed substantially coaxially with said charge, the axial thickness of said barrier being substantially less than its diameter and being within the range wherein a shock pulse transmitted forwardly therethrough, by detonation of the explosive in contact with the rearward surface thereof, will be of such intensity as to initiate a central detonation front in the explosive in contact with the forward surface thereof.

2. An explosive charge according to claim 1, in which the barrier is formed to provide a forwardly and laterally inwardly expanding annular detonation front and a forwardly and laterally outwardly expanding central detonation front.

3. An explosive charge according to claim 2, in which the barrier is adapted to cause the annular and central detonation fronts to meet and merge into a single front having a concave, central portion.

4. An explosive charge according to claim 3, in which the barrier is formed to cause the single detonation front to impinge on the liner when the curvature of the central concave portion of the front substantially conforms to the curvature of an apex portion of the liner.

5. An explosive charge according to claim 3 or 4, in which the barrier is effective to cause a time delay in the development of the central detonation front.

6. An explosive charge according to any one of the preceding claims, in which the barrier causes formation of a high-order annular detonation front and a low-order central detonation front.

7. An explosive charge, according to any one of the preceding claims, in which the barrier is adapted to transmit forwardly therethrough a shock pulse produced therein by detonation of the explosive rearwardly thereof, the ratio of the thickness of the barrier to the effective thickness of the explosive at the rearward side of the barrier being within the range causing said shock pulse to have a velocity sufficient to detonate the explosive at the forward side of the barrier, and cause formation of the central detonation front.

8. An explosive charge according to claim 7, in which said ratio is within the range causing the shock pulse to have a velocity sufficient to initiate low-order detonation but insufficient to initiate high-order detonation of the explosive at the forward side of the barrier.

9. An explosive charge according to claim 8, in which, with an explosive having a detonation rate on the order of that of cyclonite,

and with a barrier having a shock pulse transmittibility on the order of that of steel, the ratio of the thickness of the barrier to the effective thickness of the explosive at the rearward side of the barrier is between 0.5:1 and 2:1.

10. The shaped explosive charge substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

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785,155 COMPLETE SPECIFICATION
1 SHEET

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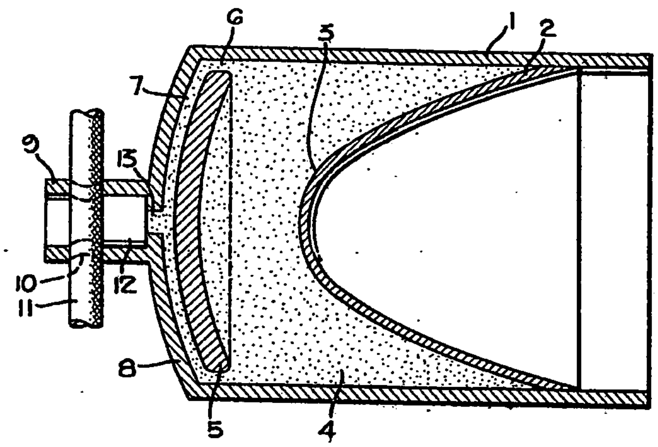

FIG. 1.

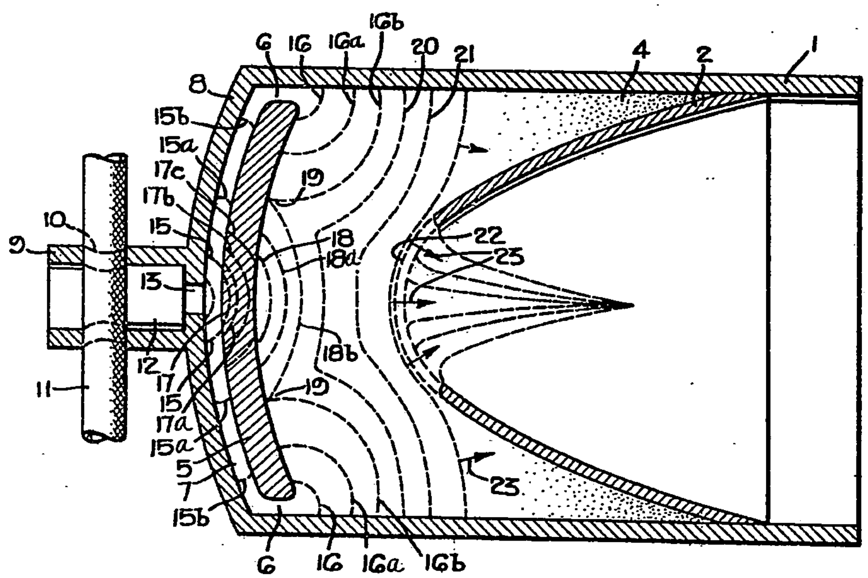

FIG. 2.